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## Self-organized InP islands on (100) GaAs by metalorganic vapor phase epitaxy

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# Self-organized InP islands on (100) GaAs by metalorganic vapor phase epitaxy

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The effect of growth temperature, deposition rate, and substrate misorientation angle on size, density, and uniformity of InP islands grown on (100) GaAs by metalorganic vapor phase epitaxy is investigated. The density of InP islands is observed to remain constant as a function of growth temperature in the temperature range of 620–680 °C. Below 620 °C the island density increases with decreasing temperature. Above 605 °C a subset of islands having a uniform size is observed. The degree of uniformity depends largely on the deposition rate and the size of the uniform islands on the growth temperature. © 1995 American Institute of Physics.

Self-organized growth of nanoscale islands has been studied extensively recently. For example, three-dimensional growth of InAs, GaInAs, and InP using growth techniques such as hydride vapor phase epitaxy (VPE),<sup>1</sup> metalorganic vapor phase epitaxy (MOVPE),<sup>2</sup> and molecular beam epitaxy (MBE)<sup>3</sup> has been investigated. However, the island structure of InP deposited by MOVPE has been previously studied only on the GaInP surface<sup>4–6</sup> and no attention has been devoted to the study of InP on GaAs surface.

Recently, self-organized InP islands were used as stressors to modulate laterally the band gap of the underlying GaInAs/GaAs quantum well (QW), thus creating quantum well dots (QWDs).<sup>7</sup> In photoluminescence (PL) studies of QWDs induced by self-organized stressors intense luminescence red shifted 105 meV from the QW peak has been observed.<sup>8</sup> Also, luminescence from up to four excited energy levels with an energy level separation of 20 meV has been clearly resolved. The observation of distinct PL peaks from excited state recombination is possible only if the strain-induced QWD potentials are uniform enough. The uniformity is determined by the size distribution of the islands on the sample surface. In this letter, the effect of MOVPE growth temperature and deposition rate on the height, density, and uniformity of the InP islands on differently misoriented (100) GaAs substrates is investigated. Furthermore, the optimum conditions for the growth of self-organized stressors are determined.

The samples were grown in a horizontal MOVPE reactor at atmospheric pressure. The details of the growth system have been reported elsewhere.<sup>9</sup> Epiready semi-insulating (100) GaAs misoriented by  $\pm 0.5^\circ$ ,  $2^\circ$ , and  $10^\circ$  to the [110] direction were used as substrates. The source materials were trimethylgallium (TMGa), trimethylindium (TMIn), tertiarybutylarsine (TBAs), and tertiarybutylphosphine (TBP). First, a 125 nm thick GaAs buffer layer was grown and then InP was deposited using the V/III ratio of 100. The growth temperature, nominal growth rate, and nominal thickness were

varied in the range of 590–680 °C, 0.25–5.5 ML/s, and 2–7.5 ML, respectively. The sample was cooled immediately after the deposition of InP. The nominal growth rate was determined from an InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As superlattice grown on InP substrate by calculating the layer thicknesses from x-ray diffraction and photorefectance measurements.

Atomic force microscopy (AFM) was used to image the sample surface. The island dimensions were measured by AFM and, for comparison, by scanning electron microscopy (SEM). The diameter of the homogeneous islands in the reference sample measured by AFM using different SiN tips and by SEM varied in the range of 100–140 and 70–80 nm, respectively. Therefore, the lateral dimensions measured by AFM are larger than the actual ones and depend on the tip shape. On the other hand, the island height measured by AFM was observed to be independent of the tip. All the dimensions mentioned below have been measured by AFM.

The deposition of InP on GaAs results in Stranski–Krastanow growth. The driving force for island formation is the large lattice mismatch. The InP islands observed in the samples can be divided into three different types. The largest islands are 50–200 nm high with a diameter of 200–800 nm. These nonuniform islands are formed only after certain nominal InP threshold thickness is exceeded and the size of the islands increases with increasing deposition of InP, which has also been observed on the GaInP surface.<sup>4</sup> The medium-size islands have a uniform size in each sample. The height of the uniform islands ranges between 12 and 42 nm and the diameter between 90 and 180 nm depending on the growth conditions. The islands of the third type are smallest, having a height of 1–6 nm, a diameter of 40–80 nm, and nonuniform size distribution. The density of islands belonging to these three types varies with growth conditions. By optimizing the growth temperature, the growth rate and the amount of deposited InP the medium-size islands have a height variation of only  $\pm 10\%$ .

Transmission electron microscopy (TEM) studies of InP islands on the GaInP surface showed that medium-size islands are coherently strained with no dislocations, whereas

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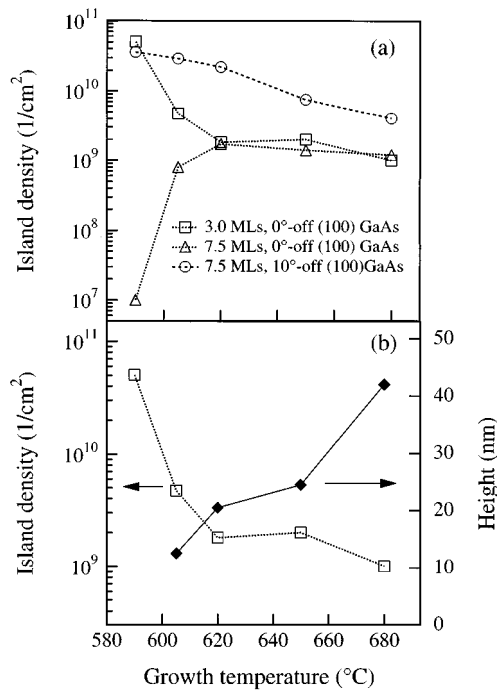


FIG. 1. (a) InP island density on  $\pm 0.5^\circ$  (100) GaAs substrates as a function of growth temperature. The coverages of 3.0 and 7.5 ML were deposited using a nominal growth rate of 1.5 ML/s. The island density in a sample with 7.5 ML InP on a  $10^\circ$  misoriented (100) substrate is also shown. (b) Island density and the height of the uniform islands as a function of growth temperature. Nominally 3 ML of InP was deposited on  $\pm 0.5^\circ$  (100) GaAs using the growth rate of 1.5 ML/s.

the large islands are partially relaxed.<sup>4</sup> When germanium was deposited on silicon, it was observed that the Ge islands were coherently strained.<sup>10</sup> The reason for the coherence was found to be the bending of the substrate below and around the island. This type of growth is called coherent Stranski–Krastanow growth.<sup>10</sup>

To investigate the island formation on differently misoriented substrates, various amounts of InP were deposited on  $0^\circ$ ,  $2^\circ$ , and  $10^\circ$  misoriented (100) GaAs. The samples were grown at  $650^\circ\text{C}$  with a nominal growth rate of 1.5 ML/s. The threshold thickness needed for the island formation was found to be about 2.5 ML on the  $0^\circ$  and  $2^\circ$  misoriented substrates and 3.5 ML on the  $10^\circ$  misoriented substrate. Below the threshold thickness only atomic steps due to the slight miscut of the substrate are observed on the  $\pm 0.5^\circ$  (100) GaAs substrate. On the  $10^\circ$  misoriented substrate the surface undulates by  $\pm 1$ – $2$  ML, which can explain the observed 1 ML larger threshold of island formation on this substrate. With all substrate misorientations the island density is highest just above the threshold of island formation. If the deposited material amount is further increased, the island density begins to decrease because of the coalescence of the islands.

To study the effect of the growth temperature on the areal density of the islands, InP was grown at the nominal deposition rate of 1.5 ML/s on (100) GaAs substrates with different misorientation at the temperatures of  $590$ – $680^\circ\text{C}$ . Figure 1(a) shows the total InP island density as a function of the growth temperature on  $0^\circ$  misoriented substrates after the

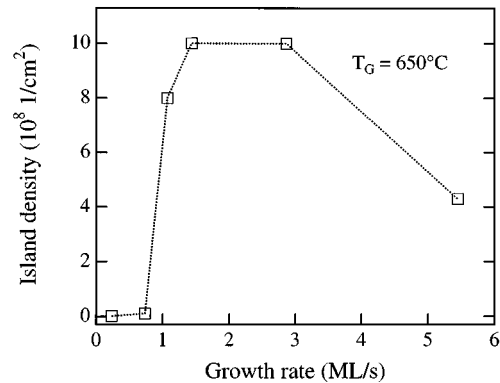


FIG. 2. Density of uniform islands after deposition of nominally 3 ML of InP on  $\pm 0.5^\circ$  (100) GaAs as a function of growth rate. The growth time was varied to keep the amount of injected material constant. The samples were grown at  $650^\circ\text{C}$ .

deposition of nominally 3 and 7.5 ML of InP. In the sample with 3 ML of InP grown at  $590^\circ\text{C}$  the island density is  $5 \times 10^{10} \text{ cm}^{-2}$ . As the growth temperature was increased to  $620^\circ\text{C}$  the island density decreased to  $1 \times 10^9 \text{ cm}^{-2}$ . At the temperature range of  $620$ – $680^\circ\text{C}$  the island density remains almost constant in the range of  $1$ – $2 \times 10^9 \text{ cm}^{-2}$ . The independence of the island density on the growth temperature at this temperature interval was confirmed by other samples grown with slightly different growth parameters. When the nominal thickness of InP was increased to 7.5 ML, the island density was reduced considerably at low growth temperatures. We expect that after the initial three-dimensional growth the additional material causes relaxation of the islands and due to the limited surface diffusion at low temperatures the growth continues as two-dimensional.

Figure 1(a) shows also the island density after deposition of 7.5 ML InP on a  $10^\circ$  misoriented (100) GaAs substrate. The island density was found to increase exponentially with decreasing growth temperature and the temperature interval with a constant island density was not observed. The island density on the  $10^\circ$  misoriented substrate is typically about a decade higher than the density on the  $0^\circ$  misoriented sub-

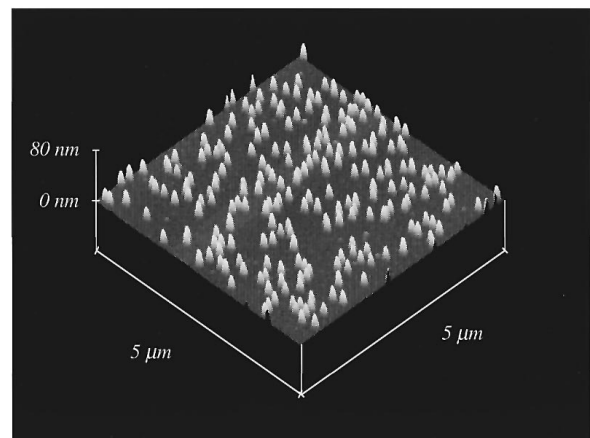


FIG. 3. Atomic force microscopy scan of a sample with nominally 3 ML of InP deposited on  $\pm 0.5^\circ$  (100) GaAs at  $650^\circ\text{C}$  with a growth rate of 1.5 ML/s. The height of the islands varies between 23 and 26 nm.

strate. Only at the growth temperature of 590 °C the island density is of the same order. The higher density on the 10° misoriented substrate indicates that the island density increases with increasing surface step density at growth temperatures above 600 °C. This effect has also been observed in vapor phase epitaxy<sup>1</sup> and molecular beam epitaxy.<sup>2</sup>

The medium-size islands in the samples grown at the temperature range of 605–680 °C were found to have a reproducible, uniform height. Figure 1(b) shows the island density and the height of the uniform islands as a function of the growth temperature after the deposition of nominally 3 ML of InP on 0° misoriented substrate. The height of the uniform islands is about 12 nm at 605 °C, and increases to 42 nm at 680 °C. The temperature dependence of the island size has also been observed in the deposition of Ge on Si.<sup>11</sup> There are several possible explanations for the size uniformity of the islands. Reaves *et al.*<sup>4</sup> attributed the uniformity to the existence of an energy barrier of dislocation formation, which must be overcome before the island can grow again. However, the temperature dependence of the island size must result from the complex interplay of the energy barriers of dislocation formation, surface diffusion, and strain energy.<sup>3</sup> At 590 °C uniform islands were not observed. The mean distance between the islands is only 45 nm, which probably prevents the sufficient bending of the substrate, which is essential for the coherency.<sup>10</sup>

Figure 2 shows the density of the uniform islands as a function of the nominal growth rate, which was varied from 0.25 to 5.5 ML/s using the growth temperature of 650 °C and the nominal InP thickness of 3 ML. The maximum density of about  $1 \times 10^9 \text{ cm}^{-2}$  is obtained within a growth rate range of 1.5–3 ML/s. In a sample grown at the rate of 5.5 ML/s the island density is only  $4 \times 10^8 \text{ cm}^{-2}$  and in addition to the uniform, medium-size islands also large islands are formed. In a sample grown with a deposition rate of 0.25 ML/s no islands are observed, which suggests that the desorption of indium from the surface is significant.

These results show that the growth conditions play an

important role in controlling the island size, density, and uniformity. An AFM image of a sample containing uniform islands is shown in Fig. 3. The density of the uniform islands is  $1 \times 10^9 \text{ cm}^{-2}$ , which can be obtained at the growth temperature range of 620–650 °C. The islands having a size distribution equivalent to this sample are ideal to be used as stressors, because (i) the large islands are absent, (ii) the small islands induce only insignificant confinement potential, and (iii) the island height variation is only  $\pm 10\%$ .

In summary, the effect of growth temperature, nominal deposition rate, and the nominal InP thickness on the InP island structure on (100) GaAs substrates misoriented by 0°–10° has been studied. The island density can be varied by changing the growth temperature and the substrate orientation. By also optimizing the growth rate and InP thickness, a large subset of islands having a uniform size is formed. The height of these uniform islands can be controllably changed in the range of 12–42 nm by altering the growth temperature.

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